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Lightning Arc Drawings – Dielectric Barrier Discharges for Artwork

S. C. Bell[1*], W. G. Enright[1], K. R. Tunstall[2] and P. S. Bodger[1]
[1]Electrical and Computer Engineering, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand
[2]School of Fine Arts, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand
*Email: scb42@student.canterbury.ac.nz

Abstract: Dielectric barrier discharges provide a simple means to generate non-thermal, non-equilibrium plasma. In this paper the use of the dielectric barrier discharge in the surface discharge arrangement in atmospheric-air under 50 Hz ac conditions is presented as a novel and flexible luminous medium for artwork. A device using the dielectric barrier discharge in this context has been termed a lightning arc drawing. In its simplest form, the lightning arc drawing consists of a conducting back-plate, a sheet of insulation and one or more conducting front electrodes. The front electrodes and the back-plate form the two terminals of the lightning arc drawing. High voltage, in the range 10–20 kV, is applied between the terminals. The discharges are clearly visible in darkness and semidarkness. They also photograph and film extremely well. A 4 m x 1 m lightning arc drawing was displayed at a recent student festival at the University of Canterbury. A high voltage test transformer was used to energize the drawings' 4.2 nF capacitance to around 20 kV. A secure area was formed and conductor clearances were established in accordance with local safety standards.

1 INTRODUCTION

In 1857 a novel type of electrical gas discharge was proposed by Siemens that could generate ozone from atmospheric-pressure oxygen or air. His first device consisted of two coaxial glass tubes and two coaxial conducting electrodes. One electrode covered the inside of the inner tube and the other covered the outside of the outer tube. The discharge was initiated in the annular gap between the two glass tubes. A radial electric field was applied by an ac voltage of sufficient amplitude to cause electrical breakdown in the gas. This gas discharge was originally called the *silent discharge* and today is commonly referred to as the *dielectric barrier discharge (DBD)*. An excellent review of the historical aspects, properties and applications of the DBD are covered in [1].

Dielectric barrier discharges provide a simple means to generate non-thermal, non-equilibrium plasma. In most gases, at around atmospheric-pressure, breakdown is initiated by a number of independent current filaments. These random short-lived micro-discharges have electron energies suited for exciting or dissociating background gas atoms and molecules. The light from such *streamer* discharges in atmospheric-pressure air in DBD configurations was first observed by Buss in 1932. The streamers have a lifetime in the order of ns to 100's of ns and are quenched due to current limitation by localized charge build-up on the dielectric layer.

One configuration of the DBD is shown in Fig 1. This is known as a volume discharge (VD) [2].

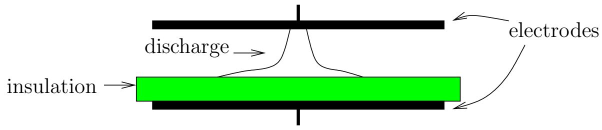


Fig. 1: DBD in the VD configuration (planar configuration).

Historically, the major application of the DBD was ozone generation, where the VD configuration in a cylindrical configuration is typically used. The free electrons generated in the discharge gap initiate a number of electro-chemical reactions resulting in the formation of ozone [3]. Large scale production of ozone for the treatment of drinking water started in Europe in the early 1900s and today there are many hundreds of ozone plants world wide, with an installed capacity totalling several 10s of MW in 1995 [4]. Industrial applications of ozone are covered in [5].

The use of the DBD for excitation of rare-gases and rare-gas halide excimers as a means to produce incoherent ultraviolet UV and vacuum UV (VUV) radiation was first published by Tanaka [6] in 1955. Today the DBD is recognised as an efficient method for the generation of such radiation which is used in various biological, physical and chemical processes. This includes disinfection of drinking and pool water [7], photochemical synthesis and degradation of organic compounds in water, photo-polymerization of organic coatings and paints [8] and photo-enhanced chemical vapour deposition. With the aid of phosphors, the VUV excimer radiation can be converted to visible light. This is the principle behind ac plasma display panels [9], which operate under a constant glow regime.

An alternative configuration of the DBD is shown in Fig. 2. This is known as a surface discharge [2].

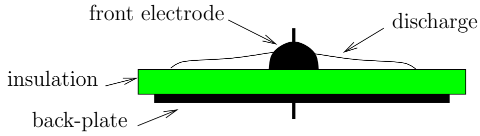


Fig. 2: DBD in the SD configuration (planar arrangement).

In this paper the use of the DBD in the SD configuration in atmospheric-air is considered as a means of producing visible corona discharge and streamers in a structured manner. This serves as a novel source of luminance that can be used, for example, in the creation of artwork and signs. A device using the DBD in this context has been termed a lighting arc drawing (LAD).

2 THE LIGNTNING ARC DRAWING

In its simplest form, the LAD consists of a conducting back-plate, a sheet of insulation and one or more conducting front electrodes. The front electrodes and the back-plate form the two terminals of the LAD. As the back-plate is much larger than the front electrodes, the discharges that result upon application of high voltage between the terminals are confined to the front electrodes, the subject of interest. In atmospheric-air, the visual intensity of these discharges is dependent on the nature of the applied voltage, the insulation thickness and permittivity, and the shape of the front electrode or electrodes [2]. The arrangement of the front electrodes determines the shape of the discharge patterns.

2.1 The Concepts

For a given back-plate and insulation system, one or more distinct types of visual activity may be observed from the front face. This depends on the number of front electrodes, the spacing between electrodes, the spacing between each electrode and the edge of the insulation, the bonding status of each electrode (bonded or un-bonded) and the operating voltage. The different types of visual activity that can occur have been categorized into drawing tools known as concepts. Each concept represents a unique way of drawing using a DBD. Knowledge of the concepts aids the design of a LAD to produce a desired overall visual effect.

2.1.1 Concept I

The visual activity accompanying the discharge surrounding a bonded electrode is known as concept I (topology shown in Fig. 3 (a)).

2.1.2 Concept II

An example of the topology where concept II can occur is shown in Fig. 3(b) and in further detail in Fig. 4. As the operating voltage is increased, streamers begin to form at the bonded electrode and creep along the surface towards the un-bonded electrode. At a critical voltage the streamers will creep along the entire distance *d* to the un-bonded electrode. This results in the formation of a bright streamer, known as a charging streamer, as the potential of the un-bonded electrode is raised to the potential of the bonded electrode. The visual activity associated with the charging streamer is known as concept II. The brightness of the charging streamers depends on the cross-sectional area of the un-bonded electrode, as well as the operating voltage and separation distance *d*. For example, charging streamers can be made brighter by the use of a larger un-bonded electrode.

2.1.3 Concept III

At higher operating voltages a power arc may form between a bonded front electrode located close to the edge of the insulation and the back-plate (Fig. 3 (c)). The visual activity accompanying this is known as concept III.

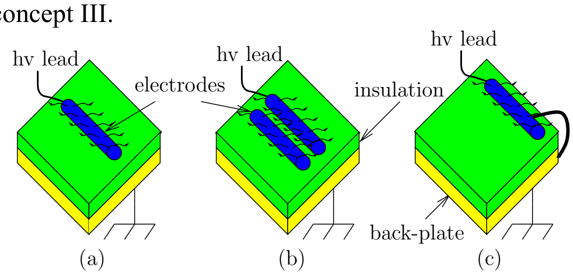


Fig. 3: The drawing concepts of the LAD. (a) Concept I (b) Concept II (c) Concept III.

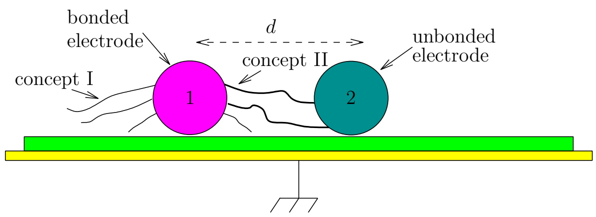


Fig. 4: Concept II details.

2.2 Construction

The continuous generation of streamer discharges at the insulation/air interface causes deterioration of the insulation and results in its eventual failure via streamer breakdown. The time to insulation failure is greatly reduced at higher voltages, where the visual intensity is much greater. The challenge, to find an inexpensive material that allows for continuous operation at voltages where intense visual activity occurs, has to date, been meet with moderate success. One promising material, commonly used in the high voltage industry, is paper/polyester film laminate. This flexible material allows for the construction of LADs in both planar and cylindrical configurations. Two successful construction techniques that use the paper/polyester film laminate are considered.

In the first, discharge occurs directly in atmospheric-air and the LAD must be vented to aid removal of ozone. One side of the insulation is sprayed with conductive paint. This side is glued and pressed to the back-plate. The pressing removes any trapped airpockets at the interface, thus minimising discharges there, and ensures the entire inner surface of the insulation is at the potential of the back-plate. The shape of the front electrode is shaded in with pencil (again ensuring an equipotential surface) before the front electrode is bonded to the insulation with glue. All concept I and III front electrodes are bonded together with thin copper wire and a single connection to the high voltage lead is made via either an alligator clip or by two rare earth magnets placed either side of the LAD. The lead to the back-plate is also connected via an alligator clip. Fig. 5 shows a LAD designed for atmospheric-air discharge. The construction materials used are summarised in Tab. 1.

Fig. 5: LAD designed for atmospheric-air discharge.

Tab. 1: Construction materials for LAD of Fig. 5.

Insulation	NMN 5-10-5 (ε_r = 2.8, V_b = 22 kV, d = 0.52 mm)
h.v. leads	15 kV, silicone insulated
Paint	Zinc-it spray paint
Adhesive	Loctite 406 glue

One alternative construction technique, which allows for drawing in concept I only, involves using tinfoil to construct the front electrodes and back-plate. Each piece of foil is spot-glued to the insulation and the resulting foil/insulation/foil sandwich is laminated using a standard office laminator. A connection to each front electrode is made by gluing a small external electrode, such as an upright sitting screw, to the surface of the laminate directly above the electrode. Electrical connections to the external electrodes and the back-plate are made in the same way as before. On operation, the connections to the internal electrodes are made by an electrical puncture of the lamination and the resulting discharge occurs *inside* the lamination. This produces a different visual effect and contains the generated ozone. Fig. 6 shows a LAD utilising this design technique.

2.3 Viewing

During operation in atmospheric-air, the visible light emitted from the LAD represents a small fraction of the emitted radiation, most of which is in the UV range 300–400 nm [10]. The LADs are designed to be viewed when operating in darkness or near darkness. In these light levels, the LADs also photograph extremely well. The LADs in Fig. 7 and 8 were photographed with a Canon EOS-1D Mark II digital camera with a 1 second exposure (actual drawing sizes are 155 x 230 mm and 300 x 80 mm respectively).

Fig. 6: LAD designed to discharge within lamination.

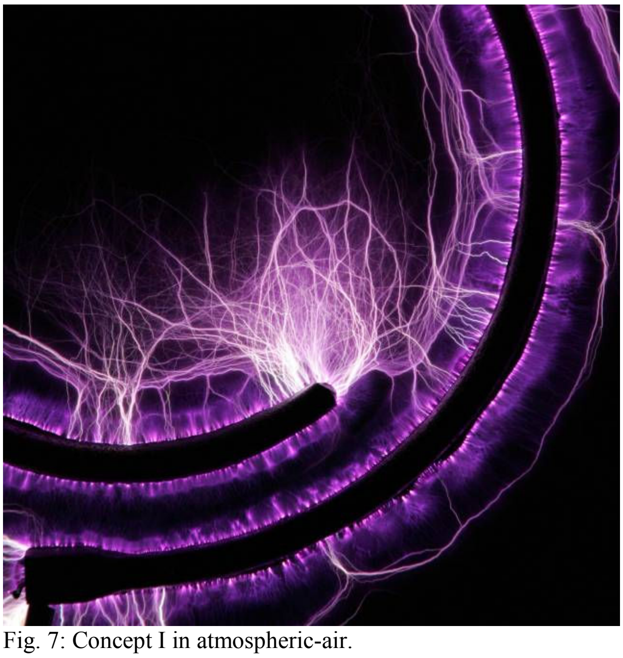


Fig. 7: Concept I in atmospheric-air.

Filming the LADs during operation is also very effective. The still image of Fig. 9, obtained from a video camera, shows a LAD using all three drawing concepts. The front face, having two concentric triangles made of copper wire as electrodes, is mounted on a triangular shaped wooden frame. The outer electrode is bonded and the inner un-bonded. The back-plate lies flush with the frame. During voltages surges of up to 20 kV the LAD operates in concept I, II and III. At this voltage level, the heat from the concept III power arcs destroys the insulation in a matter of minutes.

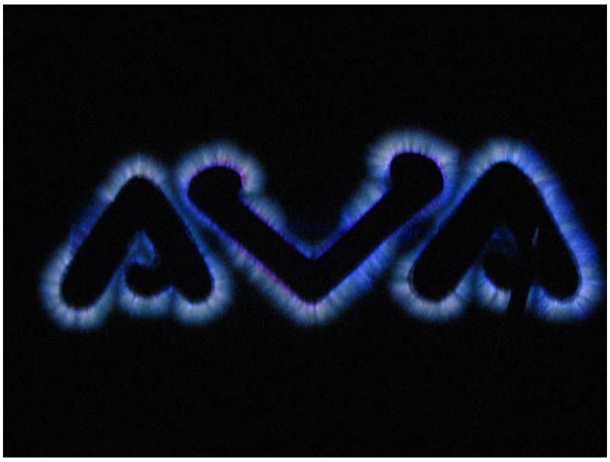


Fig. 8: Concept I inside lamination.

During concept III operation bright filaments are sometimes observed in the air surrounding the LAD. This phenomena, clearly visible in the video camera frame of Fig. 9 (labelled as "X"), has been photographed a number of times during investigations in high voltage discharge. Currently these observations are being investigated in terms of travelling magnetic fields produced during power arcs. However, they could just be a consequence of the digital filming devices.

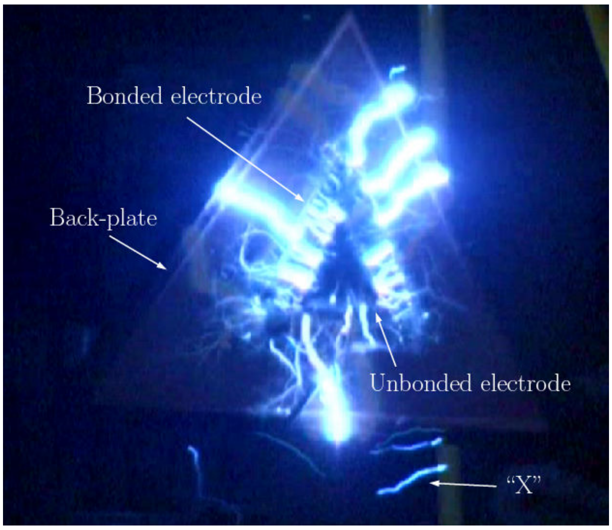


Fig. 9: Concepts I, II and III in atmospheric-air.

2.4 Electrical characteristics

The voltage and current waveforms from a sample LAD operating in concept I and III are shown in Fig. 10 (cross-sectional area = 0.224 m^2, operating voltage = 8.2 kV). The current waveform has both sinusoidal and discharge components and is consistent with what has been reported in existing literature (e.g., [11]). The sinusoidal component is due to the capacitive nature of the LAD and tends to dominate, especially for drawings with electrodes of large cross-sectional area. The discharge component appears as spikes that coincide with the first and third quarters of the voltage waveform.

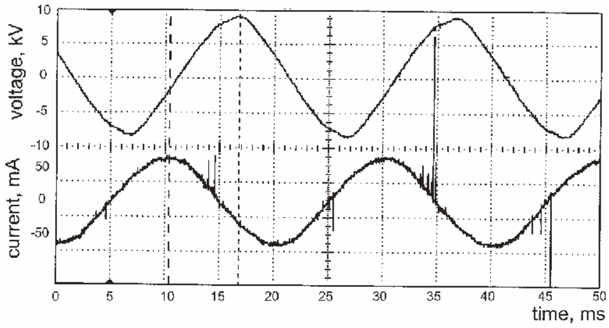


Fig. 10: Voltage and current waveforms in concept I.

As a first approximation, the load characteristic of LADs operating in concept I can be represented by an equivalent circuit consisting of a single capacitance C. This capacitance is estimated by applying the parallel plate equation,

$$C = \varepsilon_0 \varepsilon_r A / d \tag{1}$$

Where $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m is the permeability of free space, ε_r is the relative permeability of the insulation, d is the insulation thickness and A is the combined cross-sectional area of the front electrodes.

This approach, while much simpler than the typical DBD equivalent circuit (e.g., [12]), does not account for the discharge. It provides a means of estimating the RMS operating current and gives an indication of the required transformer VA rating.

Estimated and measured capacitances for two concept I LADs operating in atmospheric-air are compared in Fig. 11. The assumption of no real power loss during operation was made to determine the capacitance from voltage and current measurements. The observed increase in capacitance with voltage is consistent with existing literature (e.g., [2]) and can be explained by considering that the streamers increase the effective cross-sectional area of the front electrodes at higher voltages.

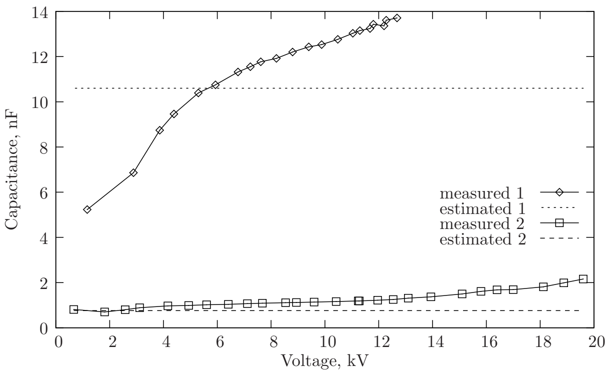


Fig. 11: Capacitance variation with voltage.

The voltage range for LADs operating in atmospheric-air are presented in Tab. 2. The corona and streamer inception voltages are defined as the minimum voltage at which corona or streamers are visible in complete darkness. They are subjective and approximate only. The electrode geometry (for example the presence of sharp edges) also has some influence on the inception voltages.

Tab. 2: LAD voltage operating limits.

Operational status	Voltage (kV)
Corona visible	1.5-2.5
Streamers visible	8.5-10
Typical operation	10-18
Maximum	~20

Knowledge of how the streamer creepage distance changes with voltage is useful in designing LADs to draw in concept II and concept III.

2.5 Power supply

Prior research found a strong dependence between the plasma excitation frequency and the rate of decomposition of contaminants in atmospheric-air in the frequency range of 50 Hz – 50 kHz. At higher frequencies the increased power density of the plasma resulted in increased decomposition rates, although the discharge ignition voltage was independent of frequency [13]. The expected increase in visual activity with increasing plasma density suggests operation of the LAD at frequencies much higher than mains frequency would allow for operation at lower voltages, with the possibility of reducing insulation failures. Such an approach was taken with ozone generators. Traditionally operated from mains frequency at around 20 kV, modern ozone generators utilise power semiconductors with switching rates of 0.5–5 kHz to operate at reduced voltages levels of around 5 kV [2].

Despite this, the current approach is to drive the LADs at 50 Hz ac via a 15 kV neon transformer connected to the 230 V mains supply. Drawing intensity is varied by making voltage adjustments with a variac, as shown in Fig. 13. The neon transformer's secondary current rating of 50 mA places an upper limit on the total cross-sectional area of the front electrodes to 0.22 m^2 for 15 kV operation using NMN 5-10-5 insulation (obtained using (1)). For larger transformer LADs a high voltage test transformer can be used.

To match the neon tube characteristic, neon transformers are designed with a high secondary leakage reactance. This limits operational current and provides short circuit withstand capability. When used to drive a LAD, partial series resonance occurs between the capacitance of the LAD and the neon transformer's secondary leakage reactance. The output voltage is therefore dependent on the cross-sectional area of the LAD as well as the input voltage, as shown in Fig. 14.

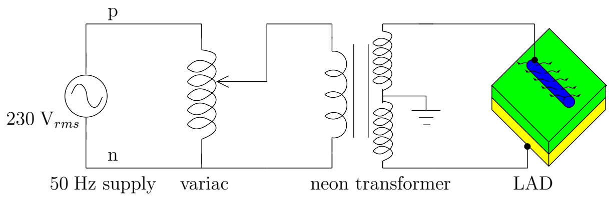


Fig. 13: Experimental setup.

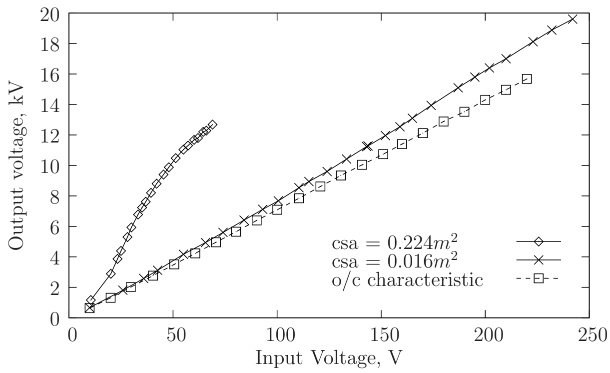


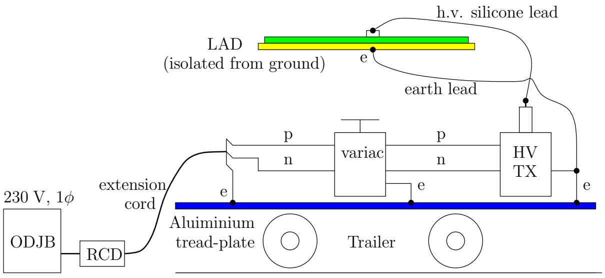
Fig. 14: Neon transformer voltage characteristic with LAD load.

2.6 Application

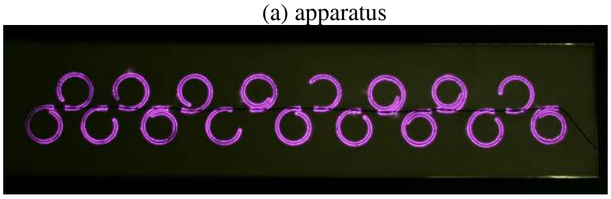
A LAD was displayed in the main entertainment room of the University of Canterbury Students' Association (UCSA) Orientation Festival at the University of Canterbury in February 2005. The sculpture, designed and built by local Fine Art student Kerry Tunstall, was based on a scaled-up version of Fig. 5. The 1 m x 4 m x 2 mm aluminium back-plate was covered in NMN 5-10-5 insulation paper and seventeen "swirl" shaped objects, with a total cross-sectional of 0.090 m^2, served as front electrodes.

The sculpture, held together with a wooden frame, was situated beside glass windows just outside the building. This ensured public safety and removed the need for the ventilation of ozone during operation. The frame was suspended from the building's structural beams with nylon rope. Displayed at night, the sculpture was clearly visible in the low light levels inside.

A variac and high voltage test transformer sat on an aluminium tread-plate located on a steel tandem axle trailer. The chassis of each was bonded to the tread-plate via a 6 mm^2 green conductor. The variac was supplied from an outdoor junction box (ODJB) via an extension cord with a residual current device (RCD) installed. A single high voltage silicone lead was used to bond the front electrodes together and make the connection to the high voltage test transformer. The connection from the back-plate to aluminium tread-plate was made with 6 mm^2 green conductor. The apparatus and operating photograph are shown in Fig. 15.



(a) apparatus



(b) operational photograph

Fig. 15: LAD at orientation festival.

A secure area was formed around the test site using danger tape and one side of the building. Clearances to the perimeter of not less than 0.45 m from exposed high voltage were observed. This was in accordance with The New Zealand Safety Manual - Electricity Industry [14] for the safe working distances for 22 kV. Earth loop tests and extension lead earthing measurements were made. These were in accordance with AS/NZS 3760:2003 [15].

During operation, access to the area was limited to the operator who was situated on the trailer. Stepping on or off the trailer only took place when the circuit was de-energised. This protected the operator from the possibility of a hazardous step potential in the unlikely event of a high voltage fault to ground.

Supply current and test transformer output voltage were measured during operation. The sculpture was operated for approximately two hours at a voltage of 17–22 kV before an insulation failure occurred. During this time the supply current did not exceed 4 A.

3 CONCLUSION

The well established DBD has been used in the SD configuration to create novel artwork and signs that are visible in darkness and semidarkness. The main issues encountered when using the DBD in this application are unwanted ozone generation and insulation failure. The issue of ozone can be overcome by either containing the discharge or with outdoor operation. Insulation failure may be reduced by operation at higher frequency or possibly with the use of an alternative insulation material. A LAD has been successfully displayed at a public festival.

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